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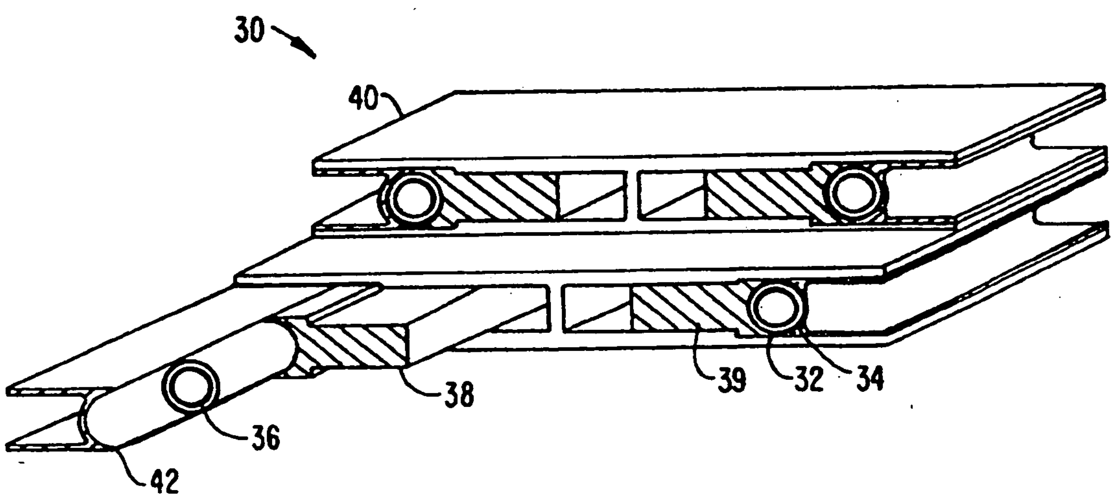


(57) Abstract

A self-supported superconducting magnetic energy storage sytem is provided. The system includes helically arranged, high current cable-in-conduit superconductor (32) located adjacent a dump shunt (38). Supporting the dump shunt (38) and the superconductor (32) is a fiber-reinforced support (40). The cable-in-conduit superconductor (32) includes a flexible tube (58) within a conduit (56) to create a space for carrying a coolant. A plurality of superconducting sub-cables (60) are helically wrapped around the flexible tube (58) and located within the conduit (56). The dump shunt (38) serves an electrical shunt to the conductor (32) during magnet quench, as heat-absorbing material to dissipate the coil's stored energy during quench, and as structural support to react all of the electromagnetic forces. The fiber-reinforced support (40) positions the elements, provides further support, and acts as an electrical insulation, and defines the coils' axial layers.

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# SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

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## BACKGROUND OF THE INVENTION

The present invention pertains generally to the field of electrical energy storage, and particularly to superconducting magnetic energy storage (SMES) systems and the way to support them.

In a SMES system, energy is stored in a magnetic field created by a current flowing in a superconducting coil (magnet). Large SMES systems for utility applications have been proposed for storing excess energy generated during off peak periods for use at a later time during peak periods. This is commonly referred to as load-levelling and was first proposed in the late 1960s in France.

In the U.S., research on SMES started in the early 1970s at the University of Wisconsin, and soon after at Los Alamos National Laboratory (LANL). A joint effort between LANL and Bonneville Power Administration (BPA) led to the development, construction, and testing of a 30 MJ (8.3 kWh)/10 MW SMES unit used to stabilize the Pacific Intertie transmission line operated by BPA. The SMES unit operated successfully for a year between 1983 and 1984. The BPA unit demonstrated the feasibility of the SMES concept for utility application.

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In 1987, the Department of Defense (DOD) became interested in SMES as a feasible power supply option for the ground-based free electron laser under development as part of the Strategic Defense Initiative. The DOD launched a program called the SMES Engineering Test Model (ETM) to demonstrate the feasibility of the technology for the dual purpose of a power supply for military applications and energy storage for the utility industry. The SMES-ETM unit was designed to store 20 MWh (72 GJ), and deliver up to 400 MW.

One problem experienced with large SMES systems is how to react the large electromagnetic forces that are produced in the system. When current is directed through the superconducting coil to produce the magnetic field, the interaction of the current and the magnetic field produces electromagnetic forces (Lorentz forces) that are exerted on the conductor. These forces need to be reacted in order to maintain the structural stability of the SMES system.

One proposed way to react the Lorentz loads produced in large scale SMES systems is to place the coil in the earth, i.e. in rock or soil. The coils are built inside a trench, and cold-to-warm supports are used to transfer the forces from the magnet to the earth.

The support structures used in early SMES systems were designed to remove as much of the stress as possible from the conductor. Such supports were deemed necessary due to the nature of the conductors. For example, one conductor design uses a superconducting wire attached to a high purity aluminum stabilizer. However, high purity aluminum has an extremely low yield stress and will flow when subjected to even moderate loads. Furthermore, high purity aluminum work-hardens as it is subjected to cyclic strain (as when the Lorentz loads vary during magnet charge/discharge). Work-hardening of the aluminum leads to an increase of electrical resistivity, thus negating the ability of the aluminum to serve as a stabilizer.

Another drawback to earth supported SMES systems is that they require the use of cold-to-warm supports. The

construction of these supports and their placement in the earth adds significant costs to the overall SMES system.

## SUMMARY OF THE INVENTION

The present invention provides a self-supported superconducting magnetic energy storage (SMES) system. The system in one embodiment may avoid cold-to-warm supports typically used to support a SMES coil. The self-supported SMES system reacts the Lorentz forces by providing extra strength to elements in a coil pack. The coil pack includes elements that can sustain cyclic strain up to their strength limit, and elements that combine strength and structural support with other functions, *i.e.* electrical, thermal, and insulation. The coil is kept at cryogenic temperatures (liquid helium) allowing for the full equivalent cool-down strain of the coil pack elements to be utilized to react the radial electromagnetic forces.

Elimination of the cold-to-warm supports greatly simplifies construction of the SMES facility. The coil, by becoming self-supported, can simply be hung from vacuum vessel walls to support its weight. Also, elimination of the conduction heat loads through the supports improves the coil's efficiency.

The SMES system in one embodiment includes a helically arranged high current cable-in-conduit superconductor. Adjacent to the superconductor is a dump shunt. The dump shunt is supported by a fiber reinforced support structure. To fully encapsulate each turn of the superconductor, a retention cap is placed adjacent the superconductor and opposite the dump shunt.

In one particular embodiment, the cable-in-conduit superconductor is constructed from a conduit that houses a flexible tube. A plurality of superconducting sub-cables is helically wrapped around the flexible tube and housed within the conduit. Each sub-cable has a plurality of superconducting wires that are helically wrapped around a copper wire. The annular space between the flexible tube and

the conduit is used for containing a coolant to cool the sub-cables.

In one aspect of this embodiment, the number of superconducting wires is five per sub-cable, and the number of sub-cables is 24. In another aspect, the conduit and the flexible tube are constructed of stainless steel. In another aspect, the conduit has an outer diameter of about 2 inches. In a further aspect, the dump shunt is constructed of aluminum or an aluminum alloy.

In a preferred embodiment, the dump shunt is an aluminum-based solid structure having means for maintaining the conduit in a substantially fixed position adjacent the dump shunt. The dump shunt also has means for transferring electromagnetic forces produced from the superconductor to the support structure. In one aspect of this embodiment, the positioning means on the dump shunt is a radial recess in the dump shunt for receiving the conduit. In a further aspect, the force transferring means of the dump shunt includes a step in the dump shunt that will engage with a step in the support structure.

To reduce heat transfer from the warm environment to the cold coil, a vacuum vessel is provided for housing the superconductor and the support structure. The vacuum vessel has an outer wall and a thermal shield between the coil and the outer wall.

To electrically connect the superconductor to an outside power grid, variable-current vapor-cooled leads are provided. Preferably, these will include a set of copper and superconductor leads that make the transition from a bath of boiling helium to room temperature. The system also includes a power conditioning system for converting incoming alternating current to direct current for storage in the magnet, and for converting outgoing direct current to alternating current.

In another embodiment of the system of the present invention, the high current cable-in-conduit superconductor is helically arranged in two radial layers to form an outer radial layer and an inner radial layer. An outer dump shunt

is positioned adjac nt and radially inward from the outer layer, and an inner dump shunt is positioned adjacent and radially outward of the inner layer. A fiber reinforced support is provided for supporting the inner and outer dump shunts. Preferably, the support is H-shaped in cross section so that it can receive the inner and outer dump shunts. In another aspect, the retention cap is provided for encapsulating each turn of the superconductor. In a further aspect, the fiber reinforced support is constructed of fiberglass and a resin.

## BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A is a schematic view of an SMES system connected to a power grid.

Fig. 1B illustrates the principles of SMES by showing the generation of a magnetic field when direct current is flowed through a coil.

Fig. 2 schematically illustrates the axial and radial Lorentz forces produced in a SMES coil.

Fig. 3A shows a schematic view of Lorentz loads in an earth-supported SMES structure.

Fig. 3B is an enlarged view of region 3B-3B of Fig. 3A.

Fig. 3C shows the radial Lorentz forces and hoop loads that are produced in a self-supported SMES structure according to the present invention.

Fig. 4 shows a coil pack assembly according to the principles of the present invention.

Fig. 5 schematically shows the net forces imposed on a dump shunt and a support structure according to the principles of the present invention.

Fig. 6 illustrates a cable-in-conduit superconductor (CICC) according to the present invention.

Fig. 7 is a cross section view of the CICC of Fig. 6.

Fig. 8 shows a SMES coil pack assembly according to the present invention.

Fig. 9 shows the preferred dimensions and proportions of a dump shunt and support structure according to the principles of the present invention.

Fig. 10 shows the cross sectional areas required per conductor turn for a dump shunt for both self-supported and earth-supported structures for different stored energies.

Fig. 11 shows the amount of fiber-reinforced support required per coil axial layer to accommodate the material requirements of Fig. 10.

Fig. 12 shows a preferred coil pack according to the principles of the present invention.

Fig. 13A shows a conductor splice according to the principles of the present invention.

Fig. 13B shows a detailed view of a half of the conductor splice of Fig. 13A.

Figs. 14A through 14C show a dump shunt splice according to the principles of the present invention.

Fig. 15 shows a fiber-reinforced support splice according to the principles of the present invention.

Figs. 16 through 19 show alternative embodiments of dump shunts using different combinations of materials that can be used with the present invention.

Fig. 20 is an isometric view of the self-supported coil inside a cryostat having thermal shields and a vacuum vessel.

Fig. 21 is a cutout of the coil in a cryostat showing the straps from which the coil is hung.

Fig. 22 illustrates different uses of the SMES system.

Fig. 23 illustrates the estimated cost savings of the SMES system according to the present invention.

## DETAILED DESCRIPTION OF THE SPECIFIC EMBODIMENTS

In a SMES system, energy is stored in a magnetic field created by a current flowing in a superconducting coil, or magnet. As shown in Fig. 1A, an SMES system can be coupled to a utility power grid 6 by power distribution lines 8. The SMES system is able to receive and store energy generated in

the power plant for future distribution to end users. Once connected to the utility grid, the SMES system can provide other benefits beyond load-levelling. The SMES system will enhance transmission line stability by dampening power disturbances. The SMES system can also be used as "spinning reserve" in lieu of an idling power plant. The SMES system of the invention is a "large-scale" system, i.e. capable of storing more than 1 MWh.

The basic principle of SMES is illustrated in Fig. 1B. A utility electrical grid 10 is used to deliver current to a superconducting wire 12. The incoming alternating current is converted to direct current by a power conditioning system (not shown). The wire 12 is coiled, and the direct current flowing through the coiled wire 12 produces a magnetic field (shown by magnetic field lines 14). If the coil 12 were wound using normal wire, the magnetic energy would be dissipated as heat in the wire's resistance. However, by using superconducting wire, the energy can be stored in a "persistent" mode, virtually indefinitely, until required.

The interaction of the current through the coil and the associated magnetic field produces electromagnetic forces (Lorentz forces) that are exerted on the coiled conductor. As shown schematically in Fig. 2, the Lorentz load for a solenoid coil has two components. One is an axial force $F_{axial}$, and the other is a radial force $F_{radial}$. The reaction of these two loads is a focus of the present invention.

In previous SMES systems, attempts were made to react these forces by placing the coil 12 in the earth and physically supporting the coils 12 with cold-to-warm support structures. One proposed theory behind the use of cold-to-warm support structures was to reduce the minimum amount of material required to react the Lorentz loads. Since the radial Lorentz loads place the coils of the conductor in tension, the minimum amount of material required to react the tensile force can be calculated using the Virial theorem which establishes:

$$M \geq \frac{\rho E}{\sigma_W}$$

with M being the minimum amount of material required to contain the radial Lorentz loads, E is the energy stored in the coil, $\rho$ is the support material density, and $\sigma_W$ is the support material tensile working stress (allowable). Attempts to support the coils with less material than what is called for by the Virial theorem have led to attempts to support the coils by the earth.

Instead of attempting to support the coils externally, the present invention is self-supported and thus falls within the Virial theorem limit.

The reaction of forces by earth supported SMES systems and the system of the present invention are shown in Figs. 3A, 3B, and 3C. In the earth supported structure of Figs. 3A and 3B, net radial Lorentz loads 16 are directed radially outward while support member loads 18, reacting the Lorentz loads, are directed radially inward. Additionally, hoop loads 24 are produced causing the coil to strain. Further, because the support members are located at discrete points 20, bending moments 22 are also produced.

By eliminating the external supports, net radial Lorentz loads 26 of the self-supported structure of the present invention (as shown in Fig. 3C) are reacted by hoop loads 28. The hoop loads in the self-supported structure 28 are greater than the hoop loads 24 of the earth-supported structure. The present invention reacts the hoop loads 28 by a self-supported SMES coil pack 30 as shown in Fig. 4.

The coil pack 30 includes a cable-in-conduit conductor 32 (CICC), i.e. a cable having superconducting properties disposed within a conduit. The CICC 32 is wound in two radial layers to form an inner radial layer 34 and an outer radial layer 36. Adjacent the CICC 32 is a pair of dump shunts 38 and 39. The CICC 32 and the dump shunts 38 and 39 are placed inside a fiber-reinforced support structure 40. A fiber-reinforced retention cap 42 is also adjacent the CICC 32 and serves to encapsulate and insulate each turn of the CICC 32.

The two radial layer d coil pack 30 shown in Fig. 4 is the particular embodiment chosen to describe the principles of present invention in detail. However, the present invention is not limited to the number of layers in which the CICC 32 is wound. For example, the CICC 32 may only have a single layer. In that event, the outer layer 36 and the dump shunt 38 would be removed. However, the resulting single radial layer coil pack would still operate according to the principles described herein. Alternatively, the coil pack 30 may be arranged with more than two radial layers depending on the desired application. In that event, the fiber reinforced support 40 would be extended as new radial layers of the CICC 32 are added. For purposes of clarity, however, the remaining discussion will describe only a two radial layered coil pack structure.

Fig. 5 shows one axial layer of the coil pack 30 of Fig. 4 with the forces experienced during operation. When current flows through the CICC 32, the radial layers experience inwardly directed forces 44 and 46 that clamp the layers together. The net radial force, i.e. the sum of forces 44 and 46, is directed radially outward relative to the center of the coil pack 30. This produces net tensile forces 48, 50, and 52 on the coil pack 30. The tensile forces 48, 50, and 52 are reacted by the coil pack 30 itself, as will be described in detail hereinafter.

In addition to the radial Lorentz loads, axial Lorentz loads 54 are produced when directing current through the CICC 32. The axial Lorentz loads 54 produce a compressive force which accumulated from axial layer to axial layer and is maximum at the coil mid-plane. As described in detail hereinafter, the axial Lorentz loads 54 are also reacted by the coil pack 30.

To react the Lorentz loads produced when current is directed through the CICC 32, the present invention uses the dump shunts 38 and 39 and the support structure 40. The outwardly extending radial Lorentz force 44 is transferred from the inner layer 34 to the adjacent dump shunt 39. In turn, the force on dump shunt 39 is transferred to the support

structure 40 by steps 41 in the dump shunt 39. The internally directed radial Lorentz force 46 on the outward layer 36 is transferred to the dump shunt 38 and to the support structure 40 by the steps 41. In this manner, all the radial Lorentz loads are reacted by the dump shunts 38 and 39 and the support structure 40, and the entire cross section acts as a composite beam.

As previously described, the resulting radial Lorentz force is produced in the outward radial direction and reacted in tension as illustrated by the forces 48, 50, and 52. This allows the coil pack 30 to be a self-supporting structure.

When the CICC 32 is cooled to cryogenic temperatures and current is placed therethrough, the net resulting outwardly directed radial Lorentz force will cause the coil pack 30 and the CICC 32 to strain. The CICC 32 is constructed so that it can withstand the cool-down strain produced during operation of the SMES system, thereby eliminating the need for cold-to-warm supports to prevent the CICC 32 from experiencing excessive strain.

An exemplary embodiment of the CICC 32 is illustrated in Figs. 6 and 7. The CICC 32 is constructed so that it is not strain limited in its cooled state, *i.e.*, it is able to withstand cyclic loads up to its strength limit. Hence, the CICC 32 can be freely strained when current is passed therethrough or discharged therefrom, thereby allowing the coil pack 30 to be self-supported. CICCs similar to the CICC 32 of the present invention have found application in some large-scale magnet applications, such as research fusion machines.

The CICC 32 is constructed of a conduit 56 and a flexible tube 58 within the conduit 56. Preferably, both the conduit 56 and the flexible tube 58 will be constructed of stainless steel, but the conduit 56 may also be constructed of Incoloy. In the annular space between the conduit 56 and the flexible tube 58 are a plurality of superconducting sub-cables 60 that are helically wound around the flexible tube 58. Preferably, for a CICC rated at 200 kA, the number of

superconducting sub-cables 60 is 24. Alternatively, the number of superconducting sub-cables 60 can be in the range from 8 to 36 depending on the application and the CICC's rated current.

Each sub-cable 60 includes a plurality of superconducting wires 62 made of a niobium-titanium allow (low temperature supercondctors) helically wrapped around a copper wire 64. Alternatively, the wire 64 can be constructed of brass or stainless steel. Preferably, the number of wires 62 will be in the range from about 5 to 8. Preferably, the copper wire 64 has a diameter of 1.6 mm, but can have a diameter in the range of 1 mm to 2 mm depending on the application. The superconducting wire 62 can be constructed of niobium compounds or alloys, and requires cooling by liquid helium.

The CICC 32 is preferably rated for carrying a current of 200 kA. At this rating, the outside diameter of the CICC 32 is preferably about 2 inches. However, the CICC 32 can be scaled to handle different current levels, and the dimensions of the CICC 32 are varied accordingly.

In operation, the conduit 56 serves as a containment barrier for liquid helium coolant. By containing the liquid helium between the conduit 56 and the flexible tube 58, a number of advantages can be realized. One advantage is that the CICC 32 operates with a high margin of stability with a minimum inventory of helium. Furthermore, the use of the conduit 56 as a helium containment allows for simplicity in fabrication, quality control and leak repair.

The CICC concept is easily scaled to very high currents and allows for high powered discharge at low coil terminal voltage. This simplifies the insulation requirements and minimizes risk.

The CICC 32 (rated at 200 kA) has been tested at the Houston Advanced Research Center where it produced a new world record in superconductivity. The 200 kA-rated conductor reached a current of 287 kA under the same conditions to be encountered in a coil (a temperature of 1.8 K and a magnetic

field of 5 TESLA) which to date is the highest current ever circulated in a superconductor.

The conductor design received further confirmation in experiments done in the National High Magnetic Field Laboratory (Tallahassee, Florida) to test assumptions regarding the magnetic protection system using a subscale test coil, and to measure the heat loads to the conductor when subjected to a varying (AC) magnetic field.

A preferred embodiment of the coil pack 30 is shown in Fig. 8. The coil pack 30 uses the same two radial layer CICC 32 described in Figs. 6 and 7 and the same dump shunts 38 and 39, support structure 40, and retention cap 42 described in Fig. 4.

As previously described, each turn of the CICC 32 is supported by the fiberglass reinforced plastic structure 40. In addition to providing support, the reinforcement structure 40 also serves to provide electrical insulation between axial layers of the CICC 32. The support reinforcement cap 42 encapsulates the CICC 32 and also provides further insulation for each turn of the CICC 32. The number of axial layers is variable depending on the desired application.

In addition to supporting the radial forces produced by the CICC 32 (as previously described), the dump shunts 38 and 39 also support the axial Lorentz loads which tend to produce an internal compression. The dump shunts 38 and 39 are preferably constructed of aluminum, aluminum alloys, or other high strength materials that can support the axial Lorentz loads.

The dump shunts 38 and 39 also serve to protect the SMES system in the event that the CICC 32 irreversibly loses its superconductivity ("quench"). During quench, the current in the coils decays, *i.e.*, all the energy stored in the coil is dissipated in the resistive parts of the conductor. Consequently, a runaway heating results and can damage the coil. To protect the coil, the dump shunts 38 and 39 provide a parallel electrical path having a low enough resistance to force the current to move out of the conductor during a

quench, and with enough thermal capacity to absorb all the stored energy without overheating.

In summary, the dump shunts 38 and 39 are employed to serve the multiple purposes of: an electrical shunt to the conductor during magnet quench, a heat absorbing material to dissipate the energy stored in the coil during a quench, and as a structural support to react all the electromagnetic forces.

The coil pack elements that carry essentially all the electromagnetic loads are the dump shunts 38 and 39 and the support structure 40. By using the following equation, the amount of material needed to react the electromagnetic loads can be determined. Without considering the axial component of the electromagnetic forces, the radial component of the Lorentz load is balanced with the coil pack 30 stresses to yield an expression for the dump shunt cross section:

$$A_{DS} = \frac{1}{f}\left[\frac{f_L D}{4\sigma_d} - \frac{E_{FRP}}{E_{Al}}\frac{A_{FRP}}{2} - \frac{E_c}{E_{Al}}A_c\right]$$

where $A_{DS}$ is the dump shunt area, $f_L$ is the net radial Lorentz load per axial layer and per unit length, D is the coil diameter, $\sigma_d$ is the design stress for aluminum, E is Young's modulus, the sub-index FRP refers to the composite support structure, Al to the aluminum dump shunt, and c to the conductor. The dump shunt area is per turn, and the FRP area is per axial layer. The factor f is to account for the axial loading in addition to the axial loading due to the radial Lorentz load. A Von Mises stress analysis gives an accurate value for f, which for the SMES coil geometries of interest is about 0.75.

Applying the above dimensioning scheme to a preferred cross section of the dump shunts 38 and 39 and the support structure 40 of Fig. 9, the plots of Figs. 10 and 11 are obtained. The numerical values of Fig. 9 are in inches and are preferred for convenience in manufacturing and fabrication. However, these values can be changed as desired depending on the particular application. Moreover, by

changing the variable dimensions of Fig. 9, yet keeping the same configuration, the concept can be used in SMES coils storing from a fraction of a MWh to thousands of MWh.

Fig. 10 shows the dump shunt cross section area required per conductor turn to make the coil self-supported for different stored energies. Fig. 11 shows the support structure cross section area required per coil axial layer to accommodate the material requirements of Fig. 10. Figs. 10 and 11 include the results for dump shunts constructed of either alloy aluminum 2219 or aluminum 6061.

More aluminum is required for the self-supported structure than is required for the earth-supported structur . However, by eliminating the cold-to-warm supports, the cost of installing the self-supported structure of the present invention is still cheaper than the concept of the previously proposed earth supported schemes. By integrating protection and structural functions in the coil pack, installation is greatly simplified and overall plant costs decrease despite the added material cost in the coil. Savings of up to 30% can be realized by this concept over the previously proposed schemes of reacting the loads through the earth.

A preferred method for constructing a SMES coil pack 130 is shown in Figs. 12 through 15. The coil pack 130 uses a cable-in-conduit conductor (CICC) 132 which is fashioned into two radial layers and as many axial layers as are needed to store the required energy. The CICC 132 is rated at 200 kA and is constructed in a manner similar to the CICC 32 of Figs. 6 and 7. The coil pack 130 as shown in Fig. 12 has the proportions corresponding to a 20 MWh unit. Supporting the CICC 132 is an aluminum dump shunt 138. The dump shunt 138 has one end that is extrusion shaped so that the CICC 132 may rest against it. The dump shunt 138 is preferably constructed of AL 2219-T851. The dump shunt 138 has steps 139 for load "locking" and load transfer through a conductor support structure 140. The support structure 140 is an integral H-shaped member made of fiber-reinforced plastic (FRP). The FRP member is a pultruded section of fiberglass and vinyl ester resin, or other like resin. Shear pins 141 are used to lock

the different structural members of the coil pack 130 in place. A FRP retention cap 142 is placed around each turn of the CICC 132. The support structure 140 and the retention caps 142 serve to insulate the coil pack 130. The shear pin 141 is preferably constructed of AL 2219. A dielectric cover 143 is placed over each shear pin 141 and also serves as insulation. Preferably, the dielectric cover 143 will be constructed of 5 ml kapton, and will have three layers.

Since the members of the coil pack 130 are fabricated in sections, splicing is necessary to produce a coil pack 130 that is continuous. Preferred splicing schemes for the elements of the coil pack 130 are shown in Figs. 13A through 15.

As shown in Figs. 13A and 13B, the CICC 132 uses a splice 150 to electrically and structurally join together sections of the CICC 132. The splice 150 allows the CICC 132 to be manufactured in discrete lengths away from the coil and subsequently brought to the coil assembly to be joined to a previously installed section of cable. The splice 150 provides mechanical and electrical continuity to the cable with low resistance.

The splice 150 includes a main splice body 151 having two halves or transition ramps 152 (one of the transitioning ramps 152 being illustrated in Fig. 13B). Preferably, the splice body 151 is constructed of brass, and include a plurality of grooves 153. Each of the sub-cables of CICC 132 is placed in a separate groove 153 and soldered to the splice body 151. The transition ramp 152 supports the sub-cables in their transition from a circular configuration within the conduit to an oval configuration within the splice 150. Preferably, a stainless steel spacer (not shown) is placed over the sub-cables and grooves 153. A helium vessel 154 is then placed over the main splice body 151 and seal welded together at welds 155. The steel spacer acts as a weld backing strip and prevents solder or flux from contaminating the weld.

The dump shunt 138 is spliced as shown in Figs. 14A through 14C. A splice 160 is initially shown in two halves in

Fig. 14A. Each half of the splice 160 has a series of steps 162. The steps 162 engage with each other as the two halves of the splice 160 are joined as shown in Fig. 14B. Since low electrical resistance is desired in the splice 160, a silver plating is applied to the steps 162 when joining the splice 160. The dump shunt 138 is shown placed in the support structure 140 in Fig. 14C. Preferably, both the dump shunt 138 and the splice 160 will be constructed of AL 2219-T851. To maintain the splice 160 in the assembled configuration, bolts 164 constructed of A286 steel are used. When in the support structure 140, a spacer 166 and a FRP cover plate 168 are placed on top and bottom of the splice 160.

To join each section of the support structure 140, an FRP splice 170 is provided as shown in Fig. 15. The splice 170 provides for both mechanical and insulation continuity. To form the FRP splice 170, each section of the FRP support 172 has a portion of FRP material removed. Joint splice plates 174 are then inserted into the FRP support 172 and are bolted to each other and to the FRP support 172 using bolts 176. Preferably, the joint splice plates 174 are constructed of A-286 steel.

To replace the removed FRP material, FRP spacer blocks 176 are inserted and secured to the FRP support 172 by shear pins 177. A joint dielectric cover 178 and a joint cover 180 are used to complete the FRP splice 170. Preferably, the dielectric cover 178 will be constructed of Kapton tape.

As previously described, the dumps shunts of the invention will preferably be constructed of aluminum or aluminum alloys. Other alternative embodiments of dump shunts are shown in Figs. 16 through 19. In Fig. 16, a dump shunt 200 for a 5000 MWh system is shown. The dump shunt 200 has a copper segment 202 and an aluminum block 204 acting as heat absorbing material (HAM).

A dump shunt 208 shown in Fig. 17 is a scaled down version of the dump shunt 200 of Fig. 16 and is designed for a 20.4 MWh system. The dump shunt 208 has a copper segment 210 and an aluminum block HAM 212. Instead of having a single

vertical member structure as in Fig. 16, the dump shunt 208 has a pair of vertical members 214.

A dump shunt 216 designed for a 5000 MWh system is shown in Fig. 18. The dump shunt 216 has an aluminum segment 218 and an aluminum block HAM 220. Vertical members 222 are also provided.

A dump shunt 224 for use with a 20.4 MWh system is shown in Fig. 19. The dump shunt 224 has an aluminum segment 226 and vertical members 228. In addition to the dump shunts shown in Figs. 15 through 19, alternative dump shunts can be made of other types of aluminum (like AL 6061), or other combinations of materials such as copper and aluminum.

The coil pack 30 and CICC 32 of Fig. 4 are housed in a vacuum vessel 250 as shown in Fig. 20. The function of the vacuum vessel 250 is to reduce heat transfer from the warm environment to the cold CICC 32. Immediately surrounding the coil pack 30 is a thermal shield 252. The thermal shield 252 has two layers and is cooled with liquid nitrogen and gaseous helium. The outer layer of the shield 252 is covered with multilayered insulation 254. Preferably, the type of insulation to be used is multi-layer insulation (MLI). The vacuum vessel 250 has an internal frame 256 and structural stiffeners 258 to provide structural integrity to the vessel 250. Preferably, the thermal shield 252 is constructed of aluminum, and the internal frame is constructed of steel. The vacuum vessel 250 is assembled in segments with three-segment modules joined together and vacuum leak tested prior to installation. The vacuum pumps and other system components used in the testing are known and well-established in the art.

The vacuum vessel 250 and the thermal shields 252, also referred to as a cryostat, is shown in Fig. 20 absent any cold-to-warm supports. The vacuum vessel 250 is shown along with straps 260 from which the coil pack 30 is hung. When charged, the coil pack 30 moves outward, which is allowed for by the flexibility of the straps 260 and the associated cryogenic connections. Preferably, the straps 260 will be constructed from FRP, and will be designed to carry the weight of the coil pack 30.

The cryogenic system maintains the CICC 32 coil at its operating temperature of 1.8 K (-456°F), the optimum temperature for large coils. At 1.8 K, the helium cryogen becomes "superfluid," with such outstanding heat transfer capabilities that the design of the coil cooling system is greatly simplified. The cryogenic system refrigeration cycle is constructed from highly-efficient, reliable equipment with a proven operating history. Such a system is commercially available from CVI, Inc. and others.

The CICC 30 is electrically connected to the outside world through a set of leads. Because the leads represent a large fraction of the heat load to the refrigeration system, the present system uses a concept for variable-current vapor-cooled leads (VCVCL) to improve efficiency. The VCVCLs are a set of copper and superconductor leads that make the transition from a bath of boiling helium to room temperature. The current flow through these leads is regulated by varying the helium level in three VCVCL modules. This enables the VCVCLs to always operate near optimum conditions.

The VCVCL system has been shown to reduce helium boil-off by as much as 70% compared with conventional leads, a saving that substantially reduces operating costs. A full-scale VCVCL module was fabricated and tested, and successfully met all operating requirements.

The CICC 32 is a DC device, yet charge and discharge are usually accomplished through an AC utility grid. Conversion between alternating current and direct current can be accomplished by a power condition system (PCS) having a reversible converter such aws the system described generally in U.S. Patent No. 4,122,512, the disclosure of which is herein incorporated by reference.

The PCS design is based on commercial hardware, and permits building a wide range of SMES systems from a common design. New technologies, such as higher power density bridges, can be introduced into the design in the future to achieve cost reduction. The PCS meets all SMES system requirements in the simplest, least expensive, and most reliable form.

The PCS circuit and control topology are based on a hybrid bridge design, using a current source inversion approach with current sharing between parallel silicon controller rectifier (SCR) and gate turnoff devices (GTO). A PCS control system is used with the SCR and GTO devices to insure proper application. Additionally, GTO interphase transformers and SCR interphase transformers are used to insure proper voltage at the GTO and SCR devices. This approach requires only one conversion level, thus minimizing hardware costs and internal losses. Advanced control features are used to regulate the behavior of this modular, hybrid design.

The interaction of the PCS with the coil and the grid was fully validated using a real-time simulator. The simulations were done for both design and off-design conditions, including those taken from previously built and tested energy storage plants (*e.g.*, the Chino battery storage plant).

A power conditioning building houses the power conditioning system equipment required to interface between the electrical power grid (and a switchyard) and the coil. A switchyard is also a part of the system. A cryogenics building houses the major components of the cryogenic and vacuum pipe pumping systems that cool the coil.

Other structures in the plant are an administration and control building, and a conductor assembly building. The assembly building houses all the equipment required to assemble the conductor and coil sections before they are installed inside the vacuum vessel.

By constructing the self-supported coil as previously described, the SMES can be site-independent, allowing for construction irrespective of soil conditions. Furthermore, the self-supported concept opens the door to a new development and demonstration path for the technology. Because of its intrinsic scalability, there is no minimum size or "threshold" in stored energy necessary to demonstrate the feasibility of larger scale plants.

The SMES is especially applicable today as environmental, economic, and regulatory forces are reshaping the way utilities generate, transport, and distribute electricity. Although electricity has always been available on instant demand with a high degree of flexibility and control, it has never been easily stored at least not in large quantities. New environmental limits on generation, the advent of renewables, deregulation and competition, and the increasingly complex nature of transmission systems, all point towards the need for reliable and cost-effective means to store and retrieve electricity.

SMES may be used as a load-levelling device; that is, to store energy in bulk to smooth a utility's daily peak demand. In that sense, SMES would be called to fill the same market niche of pumped-hydro, batteries and compressed air energy storage (CAES).

Because no conversion of energy to other forms is involved (*e.g.*, mechanical or chemical), round-trip efficiency is very high, upwards of 90 percent. Moreover, SMES can respond very rapidly to dump or absorb power from the grid, as the only limitation is the switching time of the solid-state components connecting the coil to the grid. A SMES unit can typically respond to a grid transient and achieve full power in about 100 ms (or six cycles).

Because of its fast response, SMES can provide various benefits to a utility as shown in Fig. 23. For example, SMES can be used with a transmission substation to provide transmission stability 3a, voltage/VAR support 3b, and load-levelling 3c. SMES can also be used with a generation system for frequency control 4a, spinning reserve 4b, dynamic response 4c, and load-levelling 4d. In a preferred first application, the SMES system is used to enhance transmission line stability and power quality as shown by the orthogonal area SMES-1.

SMES can be viewed as a Flexible AC Transmission System (FACTS), with the added dimension that it can insert real power into the grid. Such capability can significantly

improve transmission line dynamics, allowing to run the line at higher capacity without compromising grid stability.

An advantage of the SEMS system of the present invention is reduced capital costs compared to the previously proposed earth-suported designs. As shown in Fig. 23, the capital costs associated with the self-supported design are less than the earth-supported design for stored energies up to about 3000 MWh.

The present invention has been described in detail for purposed of clarity and understanding. It is understood that this invention is not confined to the specific instruction described herein, but it encompasses modified forms within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A self-supported superconducting magnetic energy storage system, comprising:

a high-current superconductor, said superconductor helically arranged in two layers forming an outer layer and an inner layer;

an outer dump shunt adjacent and radially inward of said outer layer; and

an inner dump shunt adjacent and radially outward of said inner layer.

2. The system of claim 1, further comprising a fiber-reinforced support for supporting said inner and outer dump shunts.

3. The system of claim 1, wherein said support is H-shaped in cross-section for receiving said inner and outer dump shunts.

4. The system of claim 3, further comprising a retention cap for encapsulating each turn of said superconductor.

5. The system of claim 4, wherein said inner and outer dump shunts are constructed of aluminum or alloy-aluminum and wherein said fiber-reinforced support is constructed of fiberglass and a resin.

6. The system of claim 3, wherein said conductor is a cable-in-conduit superconductor comprising a conduit, a flexible tube within said conduit for carrying a coolant, and a plurality of superconducting sub-cables helically wrapped around said flexible tube and within said conduit.

7. The system of claim 6, wherein each sub-cable comprises a plurality of superconducting wires helically wrapped around a copper wire.

8. The system of claim 7, wherein the number of superconducting wires is in the range from five to eight per sub-cable.

9. The system of claim 8, wherein the number of sub-cables is in the range from twelve to thirty-six.

10. The system of claim 7, wherein said conduit is constructed of steel, and said flexible tube is constructed of stainless steel.

11. The system of claim 1, wherein said inner and outer dump shunts each comprise an aluminum based solid structure having means for maintaining said conduit in a substantially fixed position adjacent each dump shunt and having means for transferring electromagnetic forces produced from said superconductor to said support.

12. The system of claim 11, wherein said positioning means comprises a radial recess in each solid structure for receiving said conduit.

13. The system of claim 12, wherein said force transferring means of each dump shunt comprises a step in each solid structure for engagement with steps in said support.

14. The system of claim 6, wherein said coolant is liquid helium.

15. The system of claim 6, wherein said conduit has an outer diameter of about two inches.

16. The system of claim 6, further comprising insulation disposed around said conduit.

17. The system of claim 1, further comprising a vacuum vessel for housing said superconductor and said support.

18. The system of claim 17, wherein said vacuum vessel comprises an outer wall and thermal shields between said coil and said outer wall.

19. The system of claim 18, further comprising variable-current vapor-cooled leads for electrically connecting said superconductor to an outside power grid.

20. The system of claim 19, further comprising a power conditioning system for converting incoming alternating current to direct current for storage, and for converting outgoing direct current to alternating current.

21. A self-supported superconducting magnetic energy storage system, comprising:

a helically arranged high-current cable-in-conduit superconductor, said superconductor comprising a conduit, a flexible tube within said conduit for carrying a coolant, and a plurality of superconducting sub-cables helically wrapped around said flexible tube and within said conduit;

an aluminum based dump shunt adjacent said superconductor; and

a fiber-reinforced support for supporting said dump shunt.

22. The system of claim 21, further comprising a retention cap for encapsulating each turn of said superconductor.

23. A power distribution system, comprising:

a power plant;

a power distribution grid; and

a current storage unit coupled to said grid, said current storage unit comprising a self-supported superconducting conductor, said conductor being arranged in at least two radial layers.

24. The system of claim 23, wherein said conductor is strainable up to its strength limit.

25. The system of claim 24, wherein said conductor is positioned within a coil pack, said coil pack having no earth support structures.

26. A method for storing energy in excess of one MW hour, comprising:

directing current through a superconducting conductor having two helically arranged radial layers; and

supporting substantially all Lorentz forces from said conductor with a frame.

27. The method of claim 26, wherein said frame comprises a dump shunt and a support structure.

28. The method of claim 26, wherein said conductor comprises a cable-in-conduit conductor.

29. The method of claim 26, further comprising coupling said conductor to a power grid.

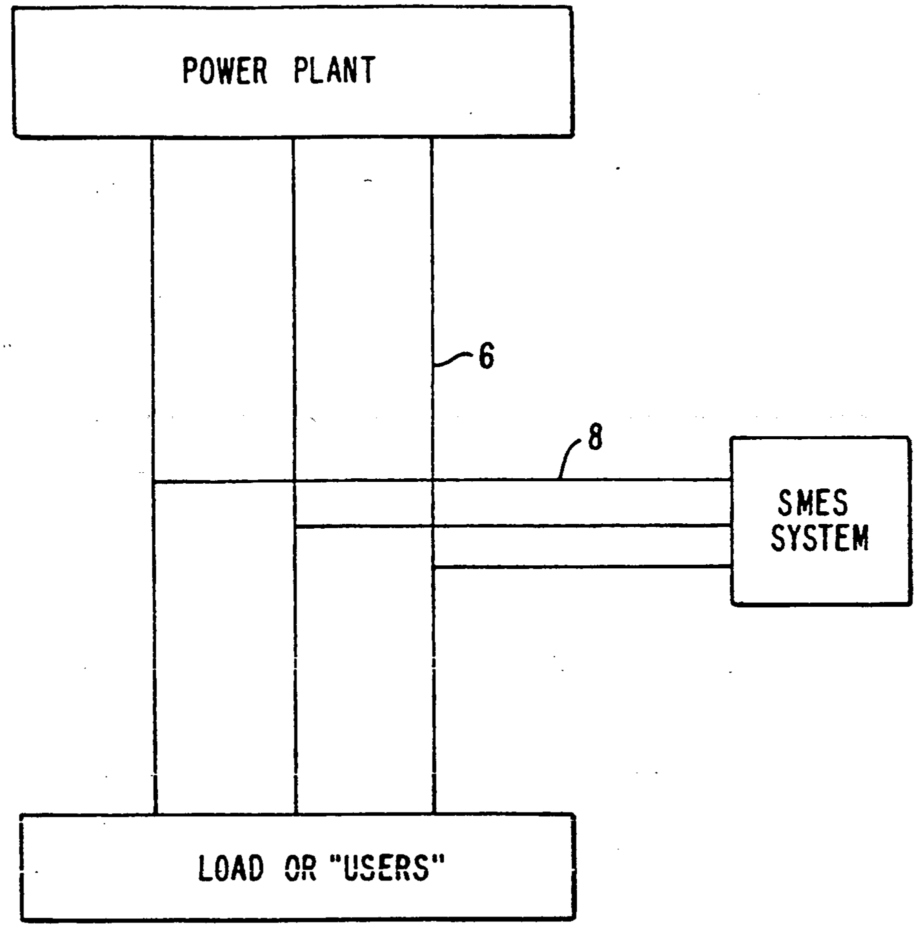



FIG. 1A.

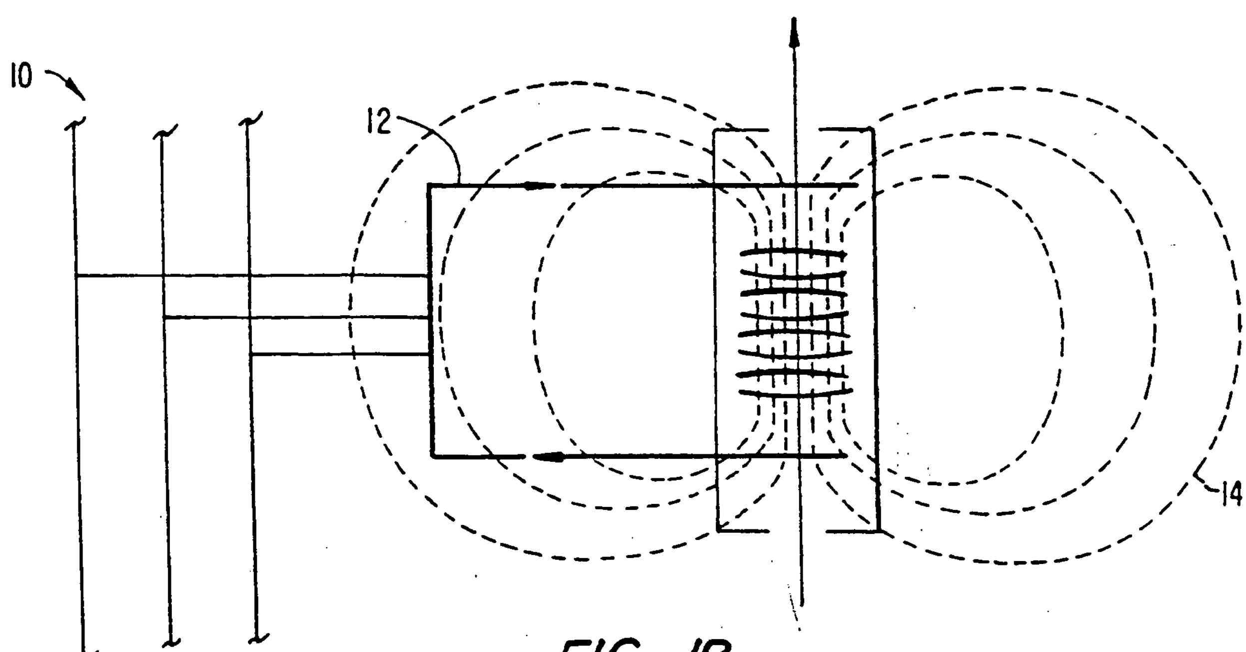



FIG. 1B.

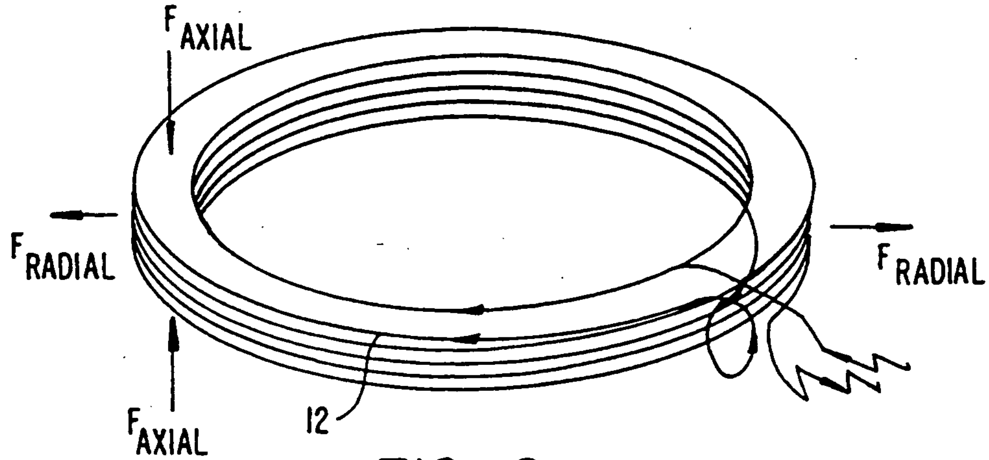



FIG. 2.

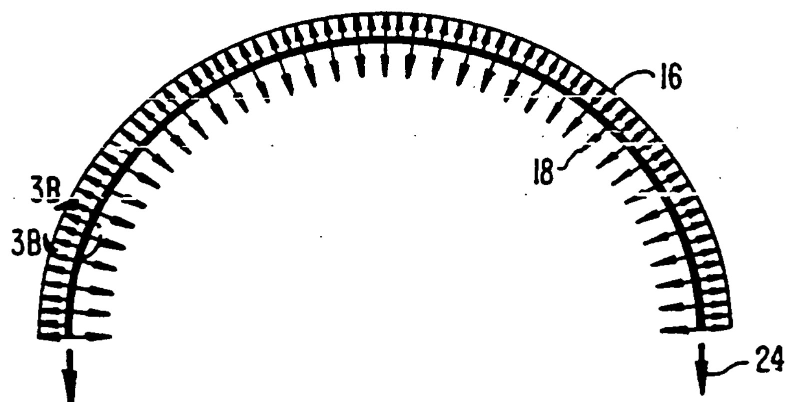



FIG. 3A.
(PRIOR ART)

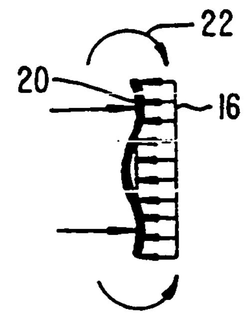



FIG. 3B.
(PRIOR ART)

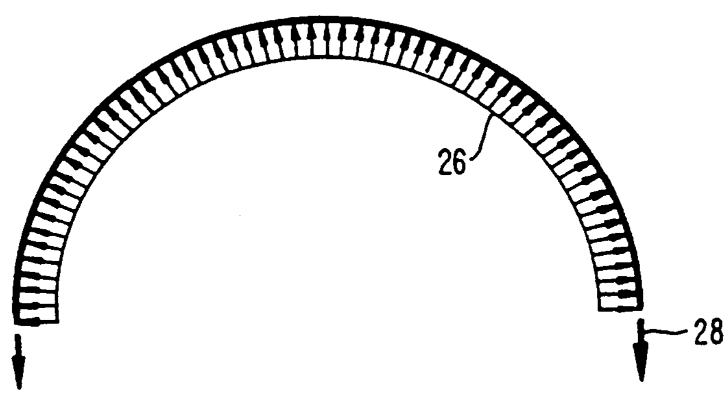



FIG. 3C.

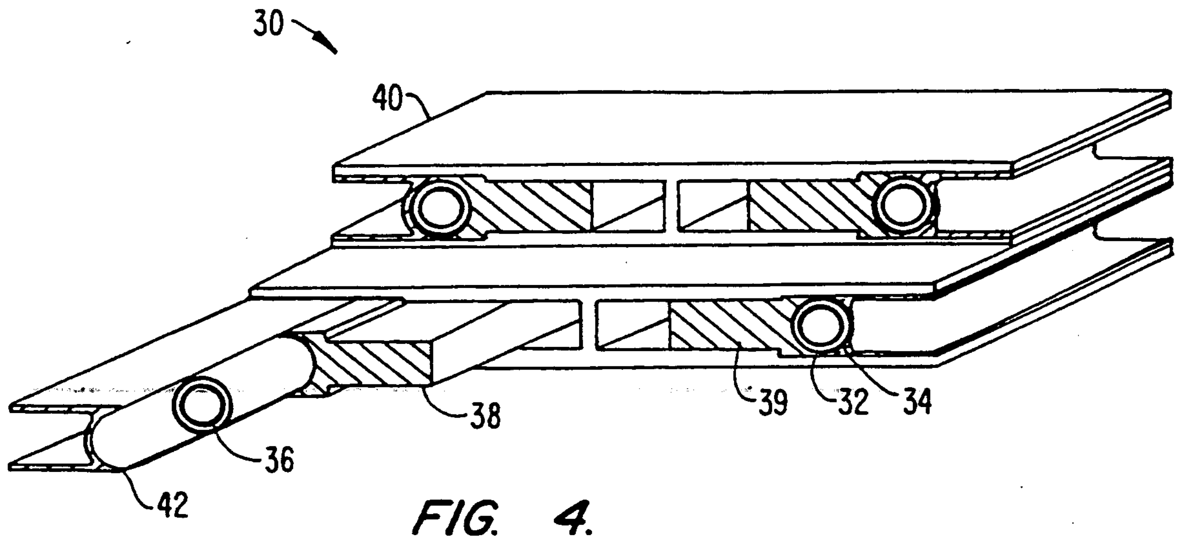



FIG. 4.

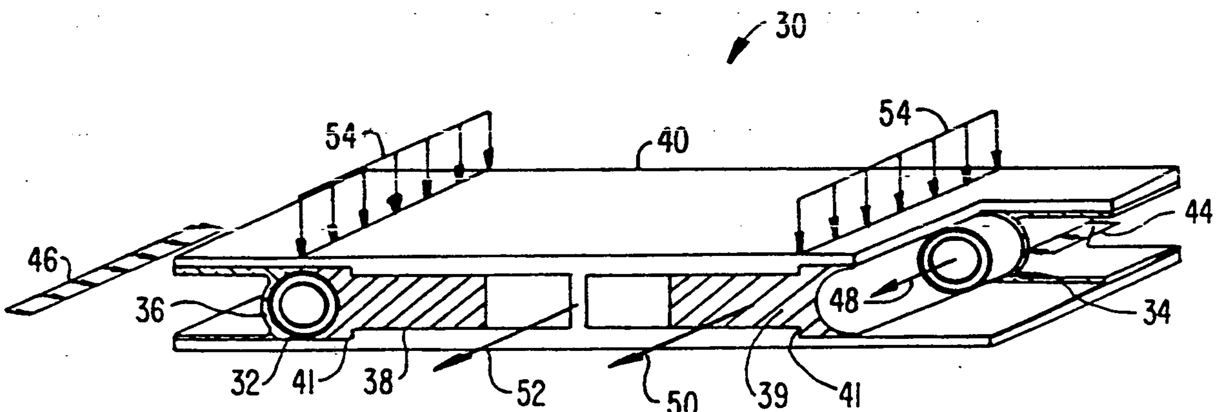



FIG. 5.

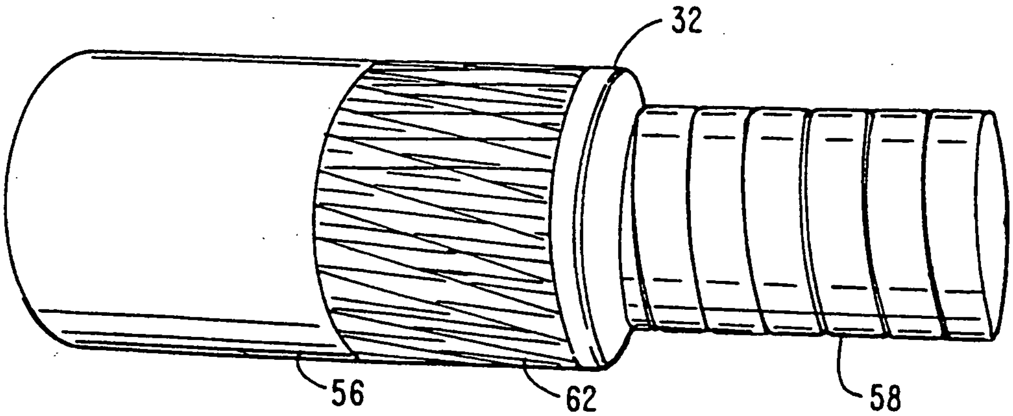



FIG. 6.

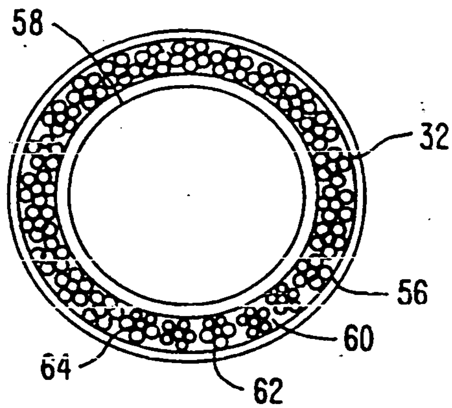



FIG. 7.

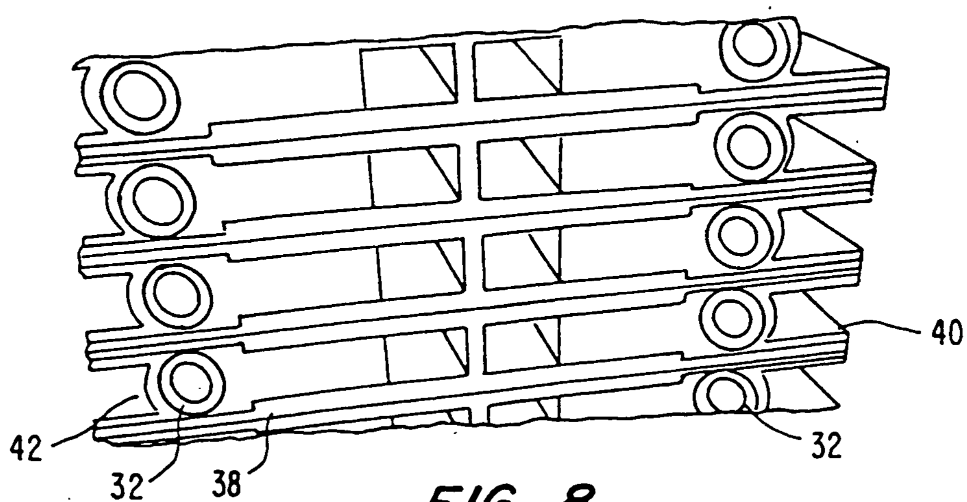



FIG. 8.

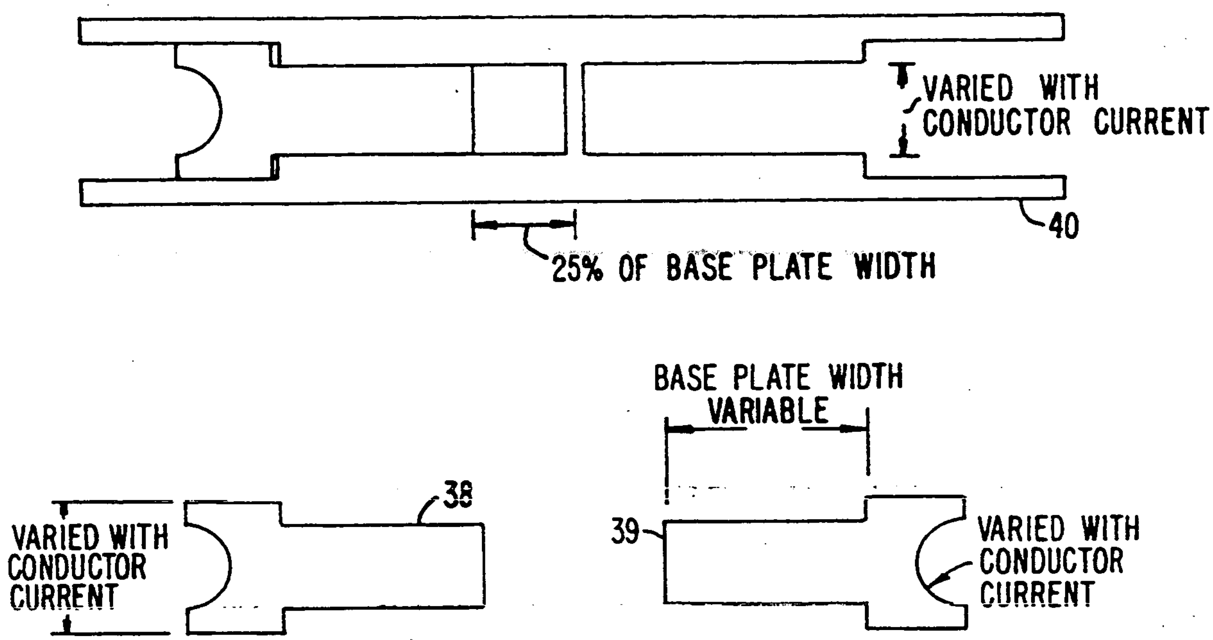

VARIED WITH CONDUCTOR CURRENT
40
25% OF BASE PLATE WIDTH
BASE PLATE WIDTH VARIABLE
38
39
VARIED WITH CONDUCTOR CURRENT
VARIED WITH CONDUCTOR CURRENT

FIG. 9.

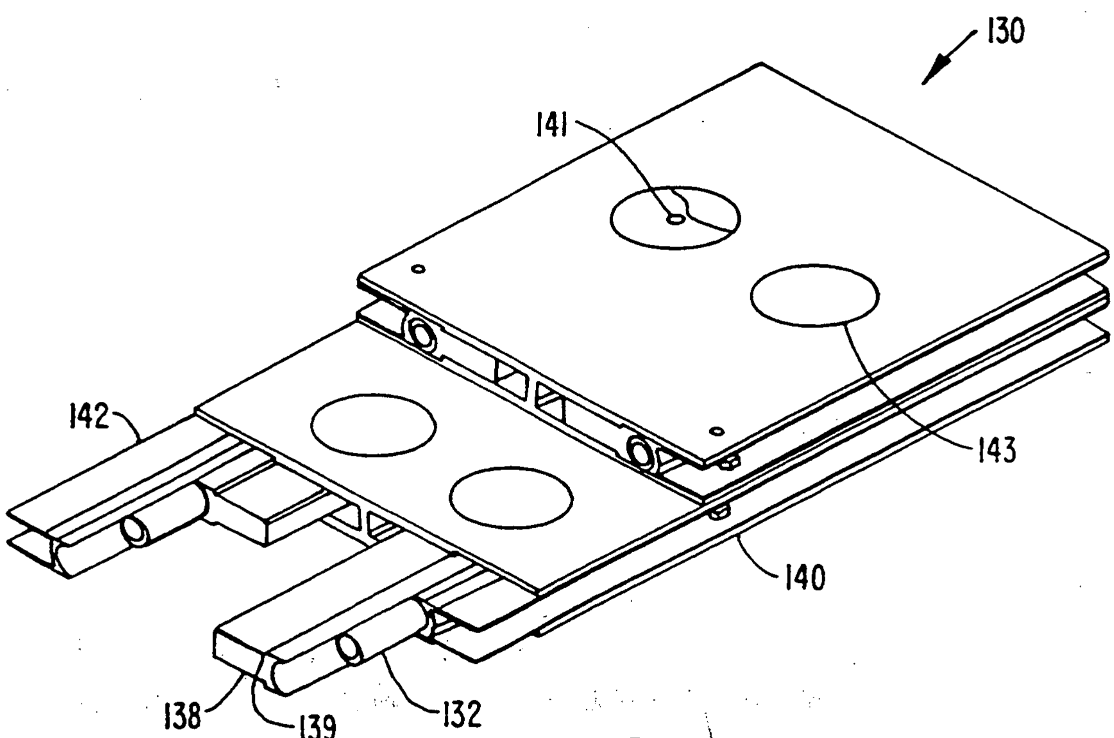
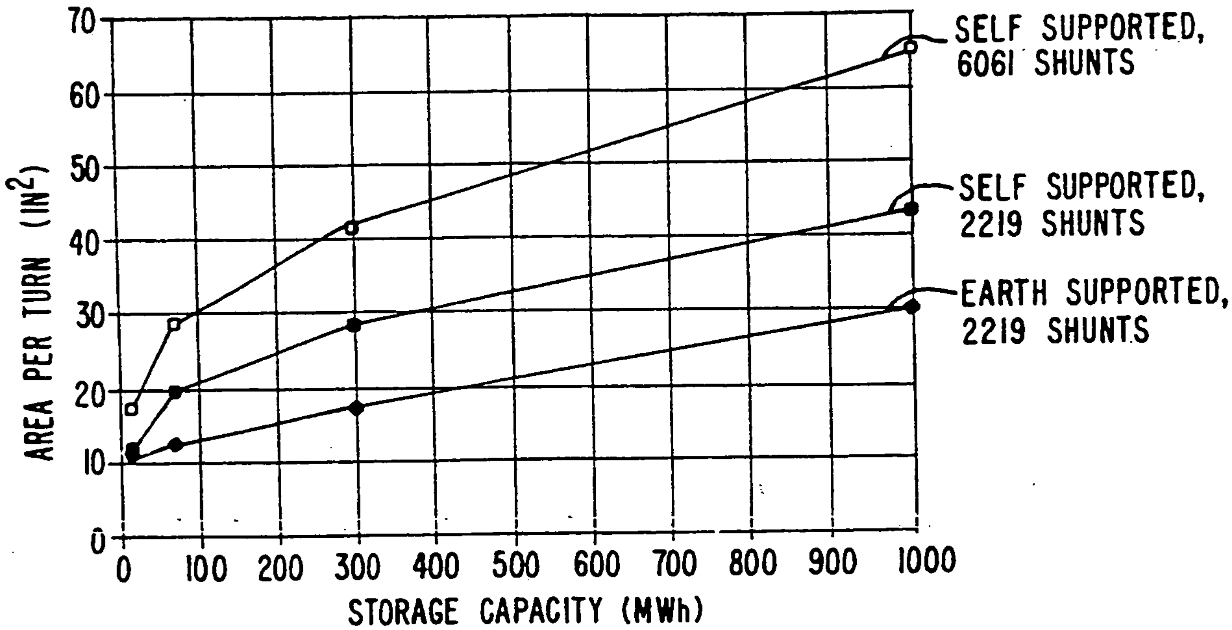
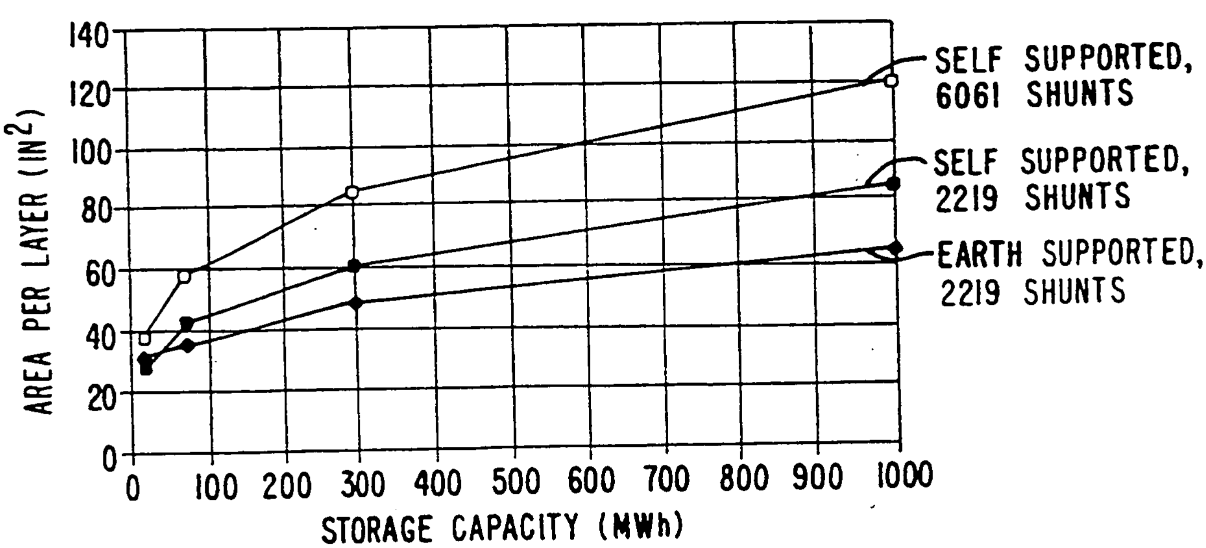

130
141
142
143
140
138
139
132

FIG. 12.



SELF SUPPORTED, 6061 SHUNTS
SELF SUPPORTED, 2219 SHUNTS
EARTH SUPPORTED, 2219 SHUNTS
AREA PER TURN (IN$^2$)
STORAGE CAPACITY (MWh)
0
10
20
30
40
50
60
70
0
100
200
300
400
500
600
700
800
900
1000


FIG. 10



SELF SUPPORTED, 6061 SHUNTS
SELF SUPPORTED, 2219 SHUNTS
EARTH SUPPORTED, 2219 SHUNTS
AREA PER LAYER (IN$^2$)
STORAGE CAPACITY (MWh)
0
20
40
60
80
100
120
140
0
100
200
300
400
500
600
700
800
900
1000


FIG. 11.

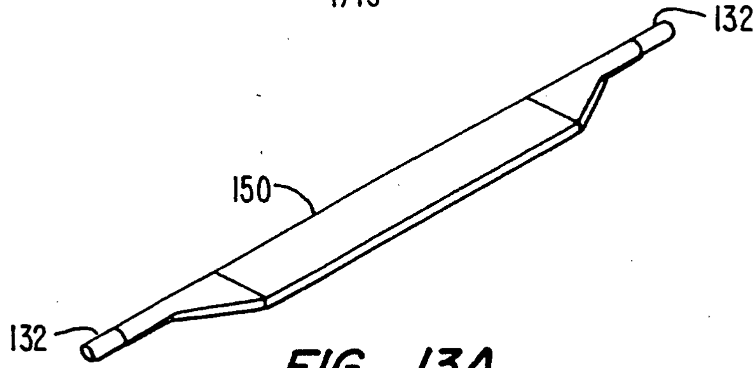



FIG. 13A.

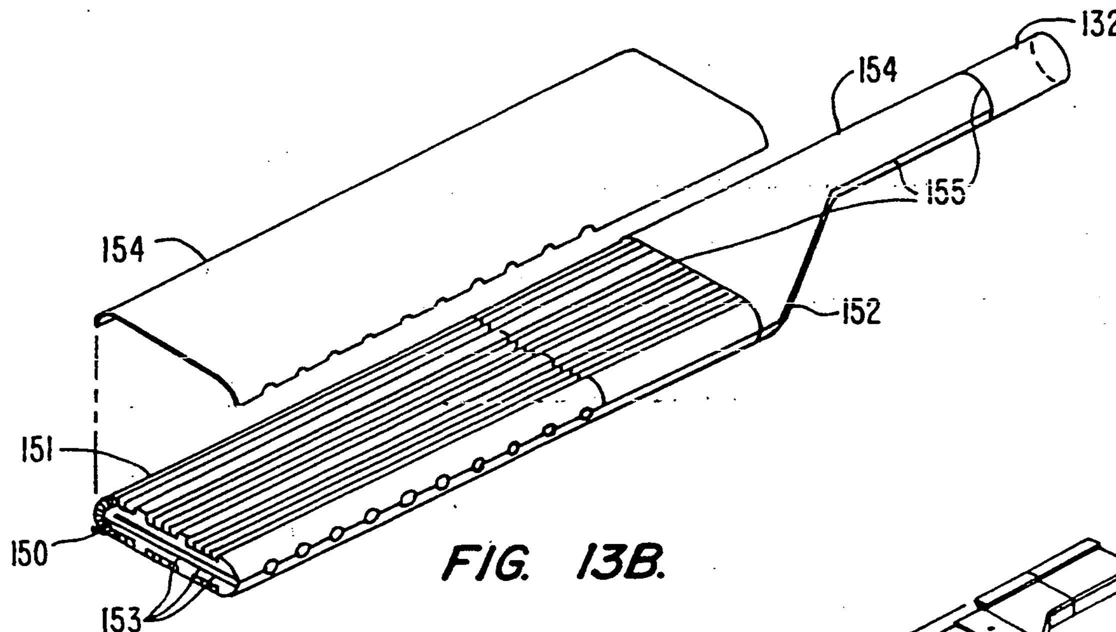



FIG. 13B.

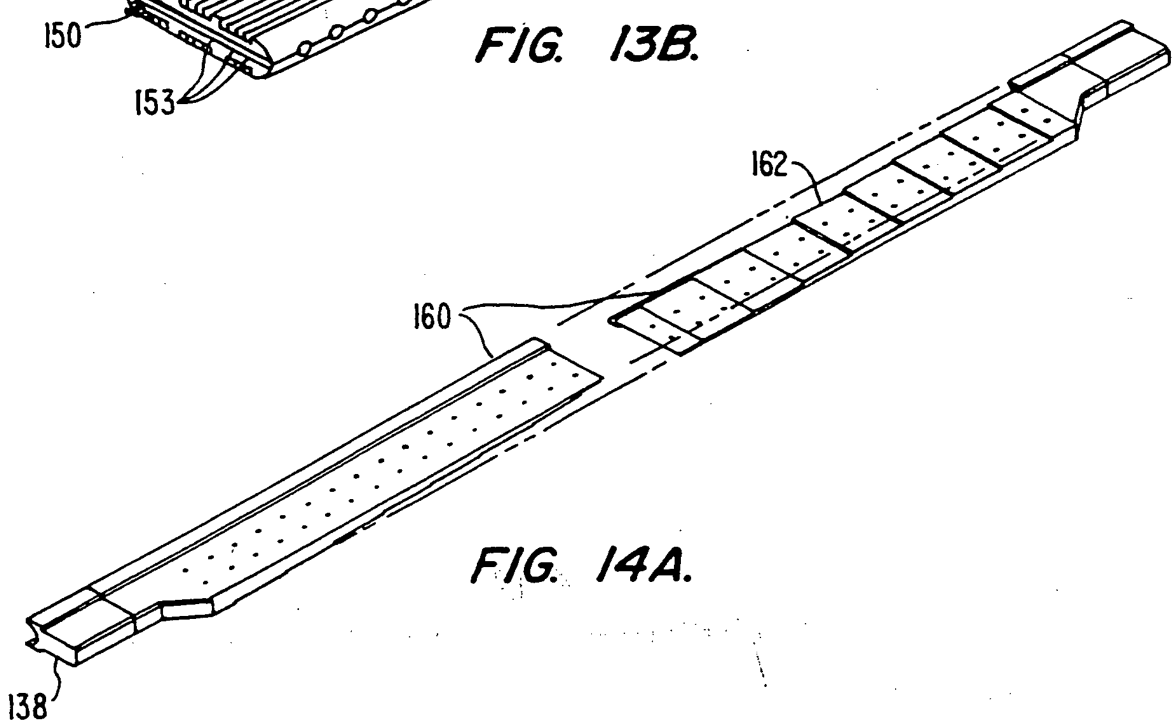



FIG. 14A.

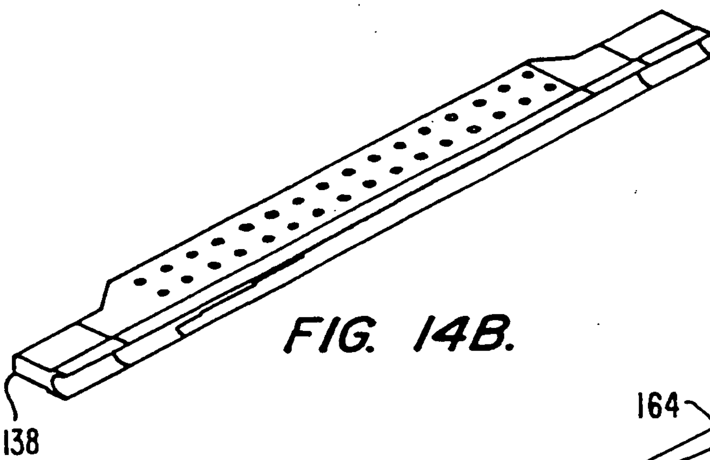



FIG. 14B.

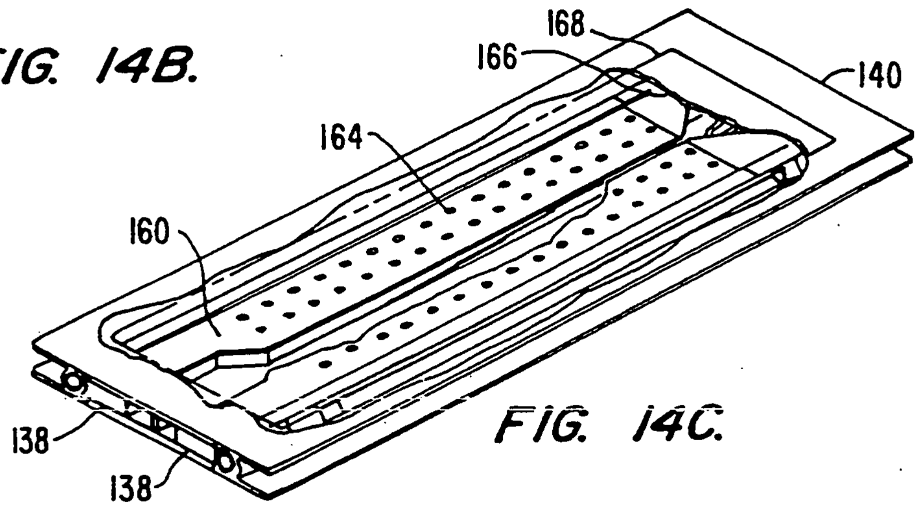



FIG. 14C.

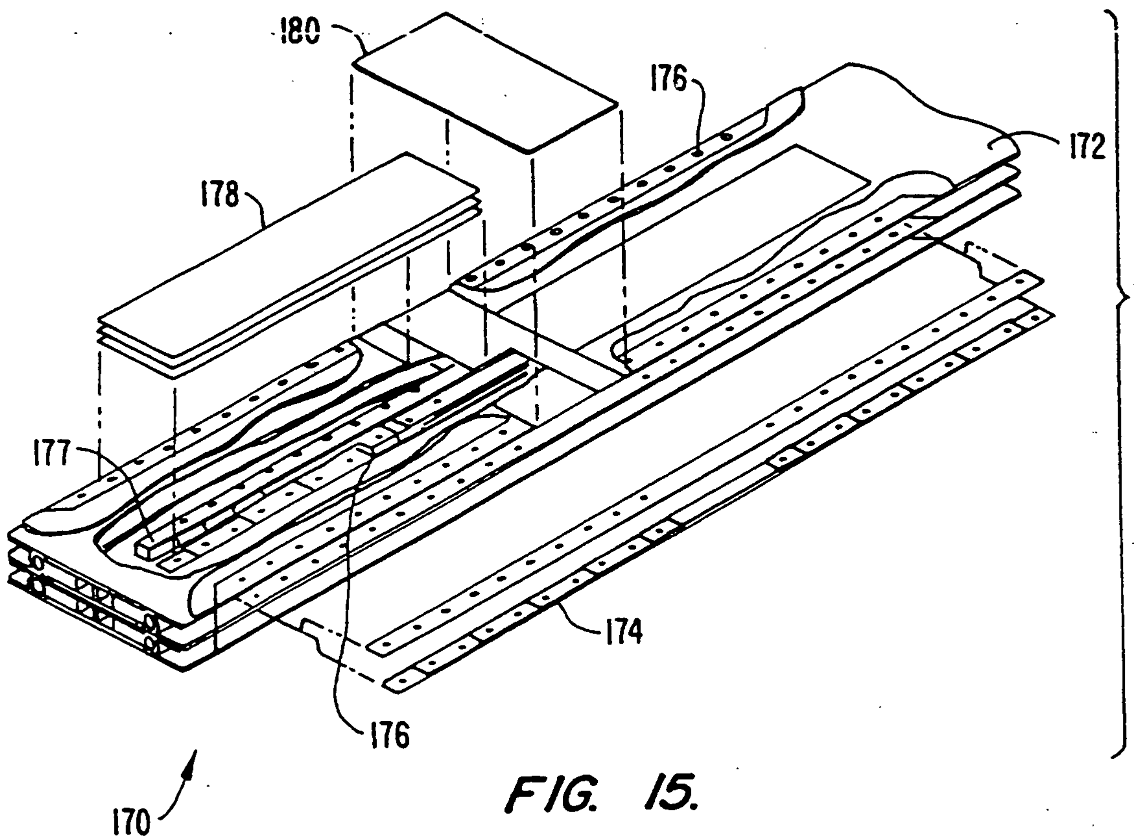



FIG. 15.

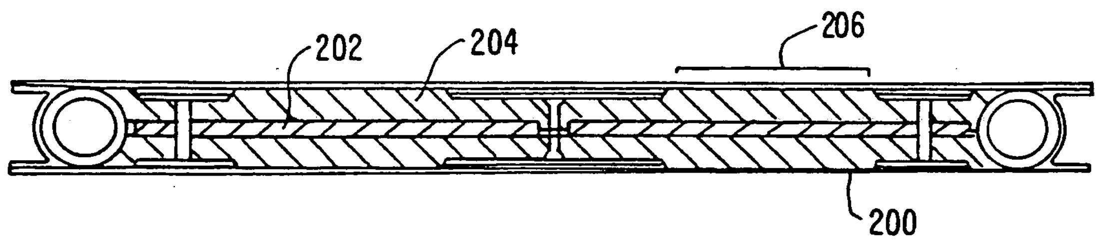



FIG. 16.

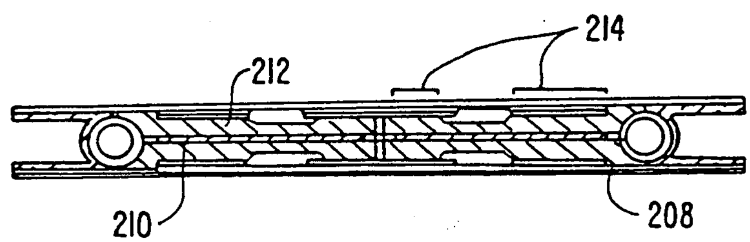



FIG. 17.

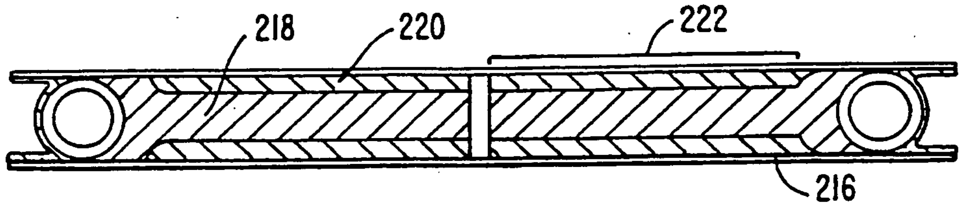



FIG. 18.

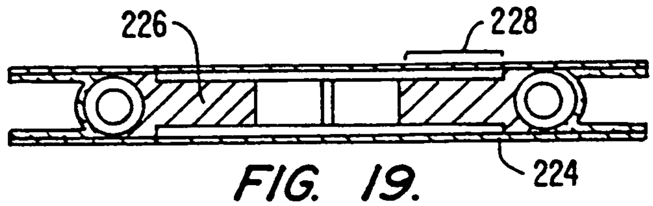



FIG. 19.

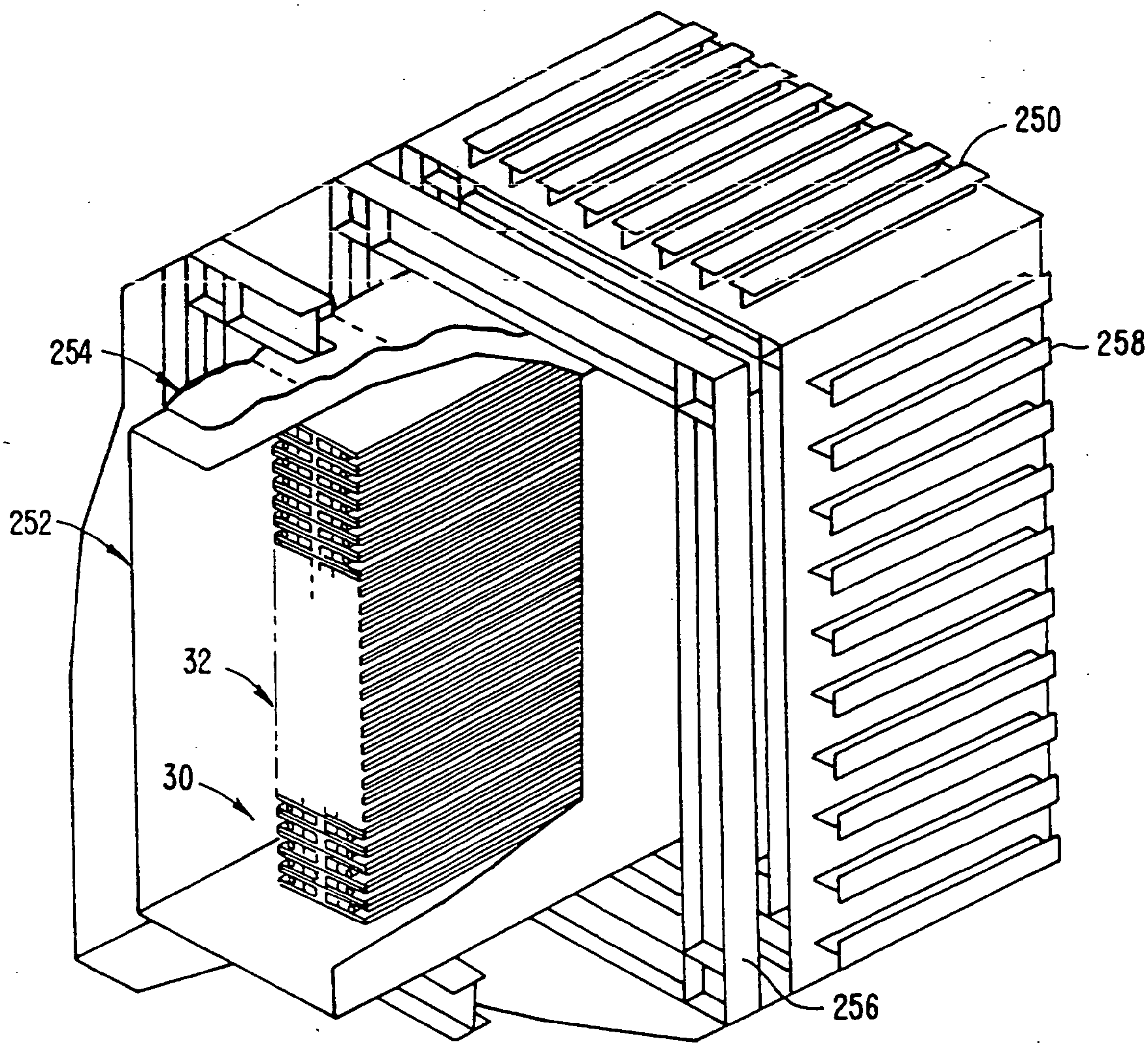



FIG. 20.

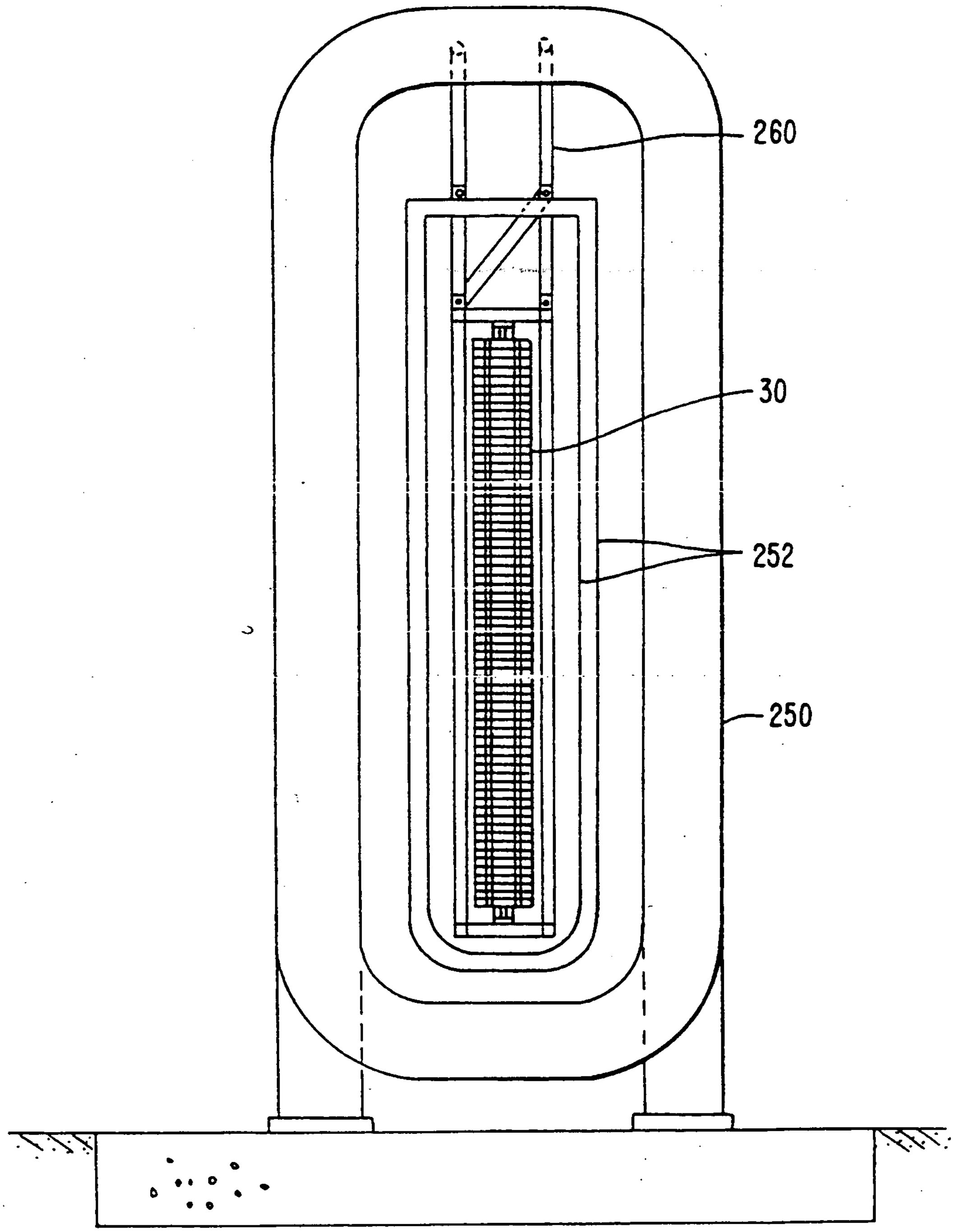



FIG. 21.

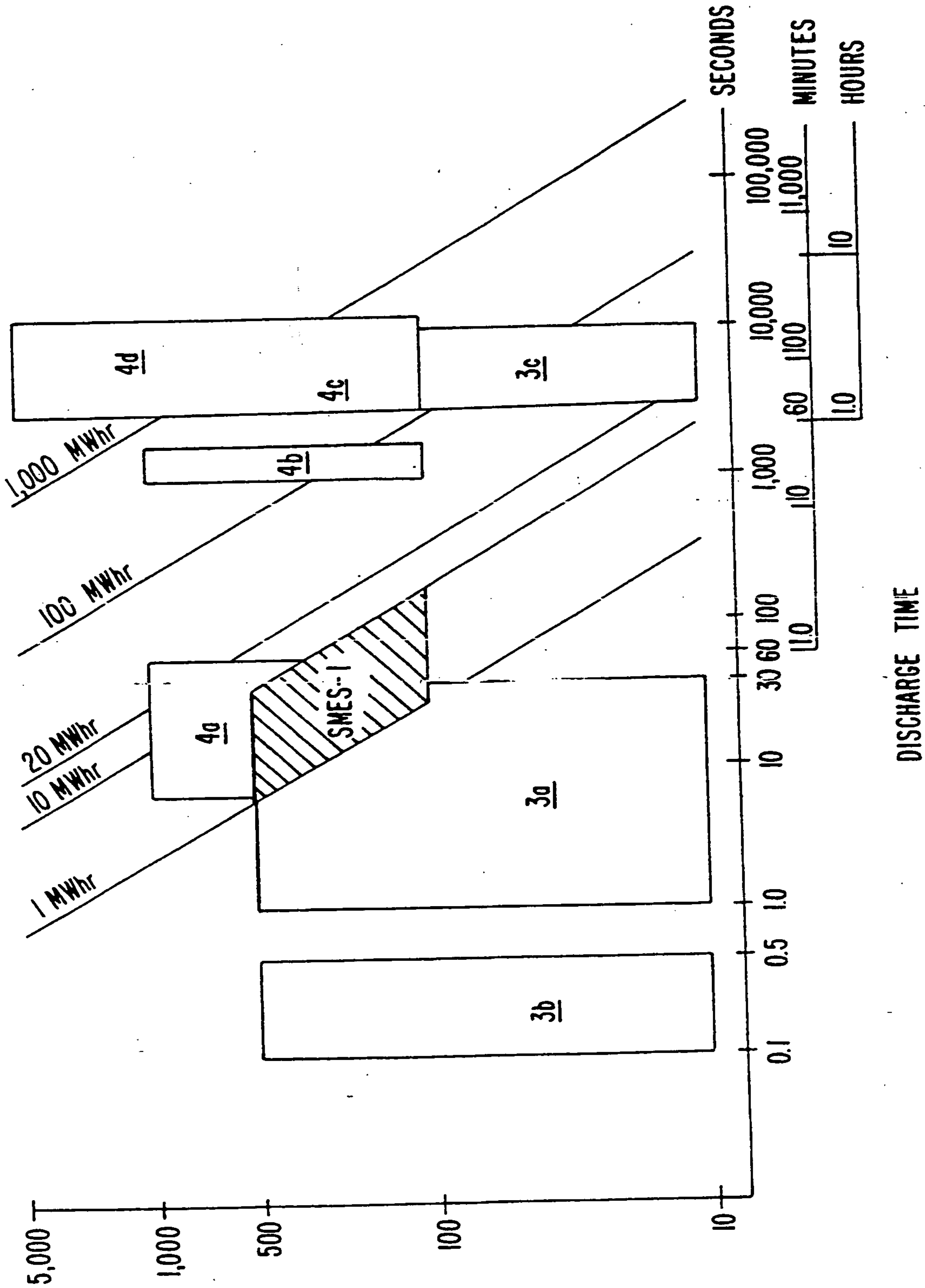

SECONDS
MINUTES
HOURS
100,000
11,000
10
10,000
1100
1.0
1,000
60
10
100
1.0
30 60 100
10
1.0
0.5
0.1
DISCHARGE TIME
4d
4c
3c
4b
4a
SMES-1
3a
3b
1,000 MWhr
100 MWhr
20 MWhr
10 MWhr
1 MWhr
5,000
1,000
500
100
10
PCS POWER - MEGAWATTS

FIG. 22.

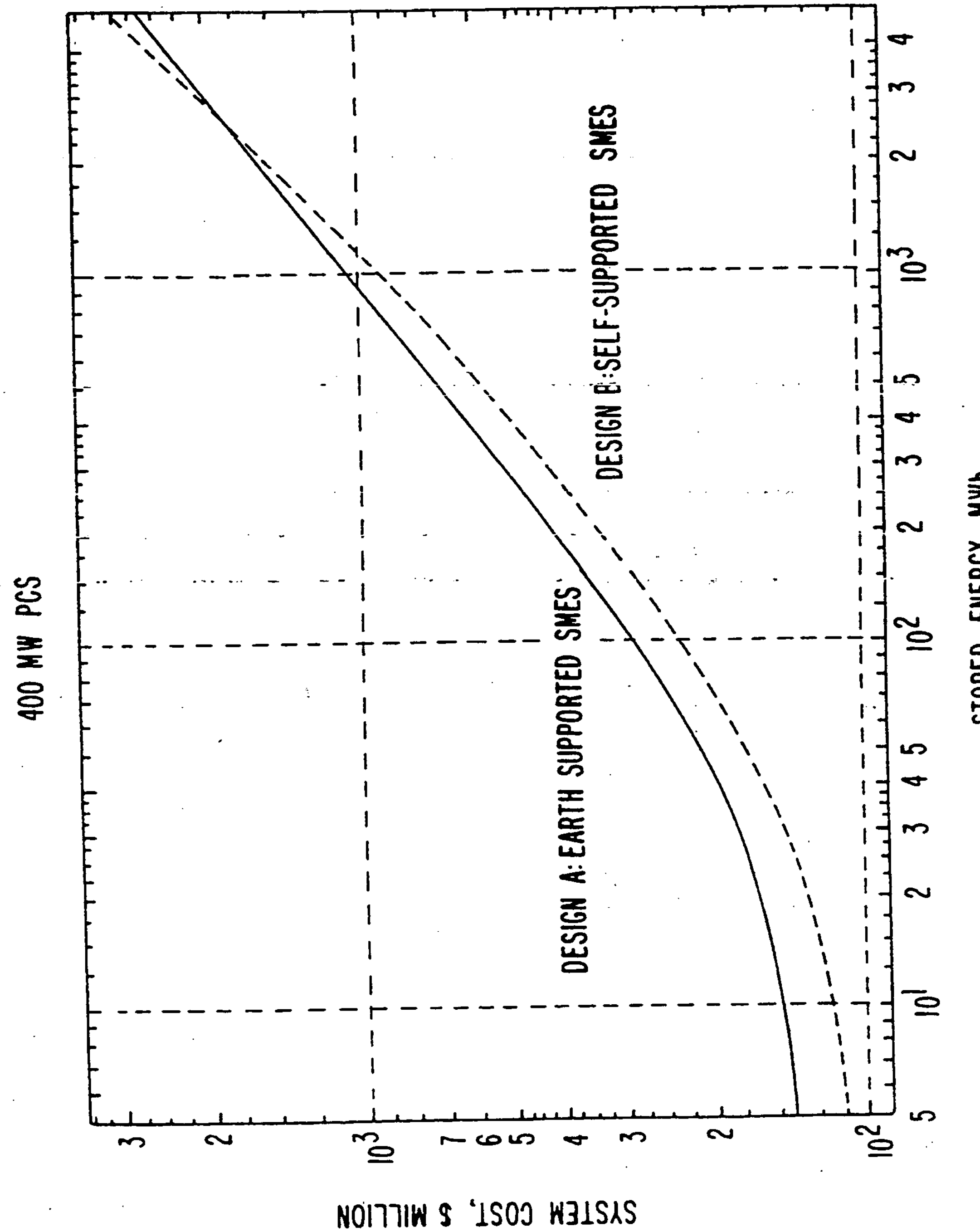

400 MW PCS
DESIGN A: EARTH SUPPORTED SMES
DESIGN B: SELF-SUPPORTED SMES
STORED ENERGY, MWh
SYSTEM COST, $ MILLION

FIG. 23.

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/01988

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01F 6/06, 36/00; H01B 12/08, 12/12, 12/00
US CL : 335/216, 323/360, 174/15.4, 505/211, 704, 705, 870, 879, 885
According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 335/216; 323/360; 174/15.4, 15.5, 125.1; 505/211, 704, 705, 869, 870, 879, 880, 884, 885, 886, 887; 336/dig.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X<br>----<br>Y | US, A, 4,622,531 (EYSSA ET AL) 11 November 1986, Figure 3. | 1-5, 11-13, 17, 23,24,<br>----------<br>18-20 |
| X | US, A, 5,173,677 (DEDERER ET AL) 22 December 1992, col. 1, lines 40-46. | 25-29 |
| Y | US, A, 4,169,964 (HORVATH ET AL) 02 October 1979, right side of Fig.1, and Fig. 3. | 6-10, 14-16, 21,22 |

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 21 APRIL 1995 | 18 MAY 1995 |

| Name and mailing address of the ISA/US | Authorized officer |
|---|---|
| Commissioner of Patents and Trademarks<br>Box PCT<br>Washington, D.C. 20231 | RAMON BARRERA |
| Facsimile No. (703) 305-3230 | Telephone No. (703) 308-0636 |

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